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Experimental characterization of the in-plane and out-of-plane behaviour of infill masonry walls

André Furtado[a]*, Hugo Rodrigues[b], António Arêde[a], Humberto Varum[a]

[a]*CONSTRUCT-LESE, Faculty of Engineering of University of Porto,Porto 4200 –465, Portugal*
[b]*RISCO-ESTG, Polytechnic Institute of Leiria, Leiria 2400 – 448, Portugal*

Abstract

The infill masonry (IM) walls are considered non-structural elements but, when subjected to earthquakes, they tend to interact with the surrounding RC frames, which can result in different failure modes depending on the combination of the in-plane and the out-of-plane behaviour. Therefore, the contribution of infill masonry panels should be considered in the structural response analysis of existing buildings, for which understanding the out-of-plane non-linear behaviour of IM walls is paramount to develop efficient strengthening solutions to prevent and improve their performance in future earthquakes and, consequently, to reduce their seismic vulnerability. In order to obtain further knowledge concerning the out-of-plane response of IM panels, an experimental testing campaign of full scale IM walls was started at the Laboratory of Earthquake and Structural Engineering – LESE by performing three experimental (cyclic and monotonic) out-of-plane tests with and without previous in-plane damage. The general specimen dimensions are representative of those existing in a large portion of the Portuguese building stock according to recent studies. The experimental campaign and test setup will be described and the experimental tests' results will be presented and discussed in the paper, namely in terms of hysteretic force-displacement curves and damage evolution.

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Keywords: Infill masonry walls, static cyclic test, out-of-plane behaviour

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1. Introduction

Typically the infill masonry (IM) walls are considered non-structural elements; however when subjected to earthquakes, they tend to interact with the surrounding reinforced concrete (RC) frames which can result in different failure modes, among which are the in-plane failure and the out-of-plane collapse. Recent earthquakes such as as L'Aquila (Italy, 2009) [1], Lorca (Spain, 2010) [2] and Emilia (Italy, 2012) [3] identified a large number of buildings that suffered severe damage or collapse had their poor performance associated with the influence of masonry infill panels.

In fact, the contribution of the IM walls to the building's seismic performance can be favorable or not, depending on a large series of uncertain phenomena, detailing aspects, mechanical properties, and others. The infills out-of-plane behaviour was observed as one of the most important critical failures of such type of non-structural elements [4, 5], as observed in Fig. 1. A few major factors causing out-of-plane instability and poor performance are the reduced support-width on RC beams and/or slabs,

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* Corresponding author. Tel.: +351913307062
E-mail address: afurtado@fe.up.pt

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normally adopted to minimize thermal bridges effect, no connection between interior and exterior panels and finally no connection to the surrounding RC frames [1].

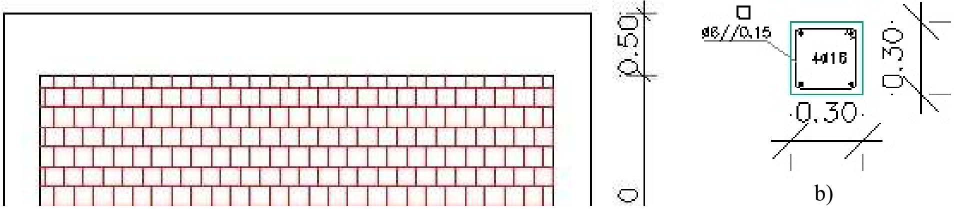
Fig. 1. IM walls out-of-plane collapses when subjected to earthquakes.

It is consensual that deeper knowledge is required concerning the behaviour of these non-structural elements when subjected to out-of-plane loadings, preceded or not by in-plane damage. Thus, experimental analysis appears as a fundamental tool allowing characterizing their behaviour through static or dynamic cyclic experimental tests. With this purpose, an experimental campaign of full scale IM walls started the Laboratory of Earthquake and Structural Engineering - LESE in order to better understand and characterize the IM walls out-of-plane behaviour with and without previous in-plane damage. For this, three experimental tests were made in original and damaged IM panels. The experimental campaign and test setup are briefly described next, as well as the tests' results which will also be presented and discussed, mainly in terms of hysteretic force-displacement curves and damage evolution.

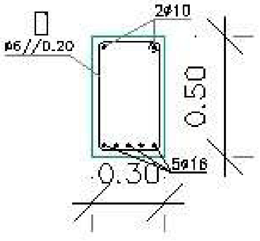
2. Experimental campaign

2.1. General overview and test specimen' description

The present experimental campaign comprised three out-of-plane tests of full-scale infilled RC frames, two of them without previous in-plane damage and one with previous in-plane damage. The general dimensions of the specimens were selected as 4.80x3.30m^2 and the cross sections of RC columns and beams are 0.30x0.30m^2 and 0.30x0.50m^2, respectively, which are representative of those existing in the Portuguese building stock [6]. Fig. 2 shows the RC infilled frame geometry, as well as the corresponding columns and beams dimensions and reinforcement detailing.



a)

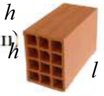


c)

Fig. 2. Infilled RC frame specimen dimensions a) general dimensions b) columns and b) beams dimensions and reinforcement detailing.

All infill panels have equal geometry with in-elevation dimensions 2.30x4.20m^2 made of horizontal hollow clay bricks as usually found in the most common masonry type in Portugal. No reinforcement was used to connect the infill panel and the surrounding RC frame. Three infill panels were built (denoted as Inf_01, Inf_02 and Inf_03), all having an external leaf (150mm thick) aligned with the external side of the RC beam. For the panel Inf_03, an internal leaf, 110mm thick, was added aligned with internal side of the beam, leaving a hollow thickness of 40mm. This double leaf panel was first tested for in-plane cyclic displacements, after which the internal leaf was removed, there remaining only the external one to be tested under the same out-of-plane loading conditions as for panel Inf_02. The summary of the experimental tests and corresponding main characteristics are illustrated in Table 1.

Table 1. Summary of the experimental tests and target maximum displacements.

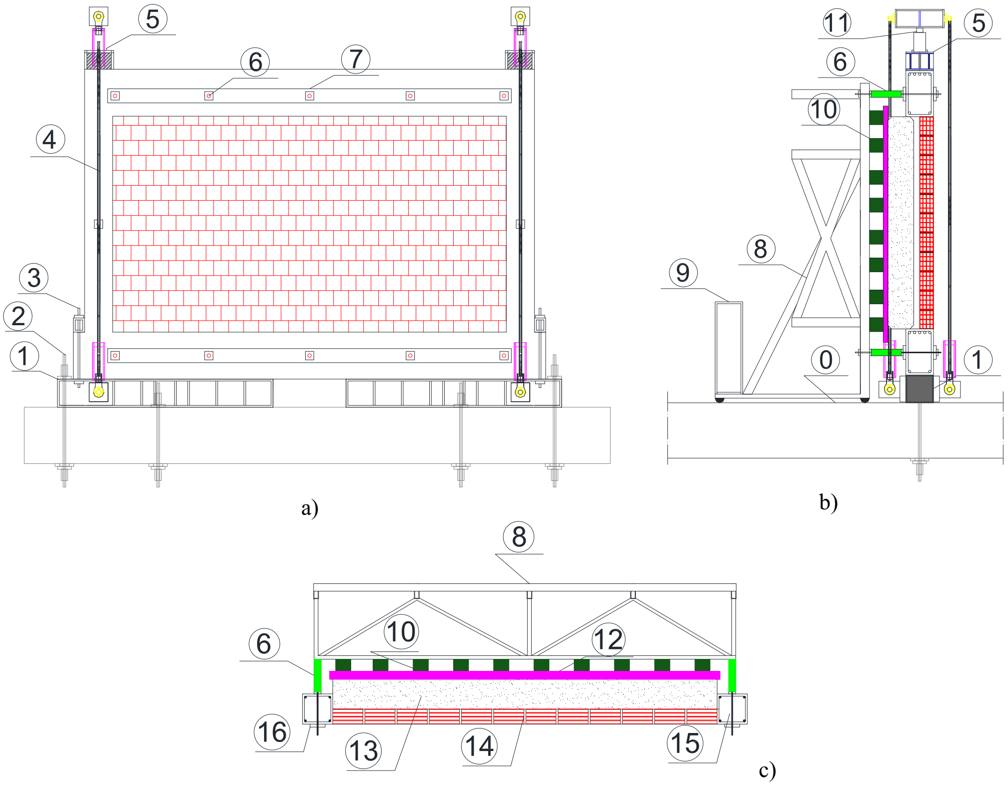
Test number	Previous in-plane drift (%)	Axial Load (kN)	Out-of-plane target displacement (mm)	Type	Number of leafs	Brick unit size *l* x *h* (mm) 
Inf_01	-	300	70	Fully infilled	1	300x200x150
Inf_02	-				1	300x200x150
Inf_03	0.5%				2(*)	300x200x150 (ext.) 300x200x110 (int.)

(*) only for in-plane testing prior to out-of-plane, for which the internal leaf was removed

2.2. Test setup description

The out-of-plane test consisted on the application of a uniformly distributed surface load through a system composed by seven nylon airbags, reacting against a self-equilibrated steel structure, as shown in Fig. 3 and Fig. 4.

This reaction structure is composed by five vertical and four horizontal alignments of rigidly connected steel bars, in front of which a vertical wooden platform was placed to resist the airbags' pressure and transfer it to the steel reacting grid elements. Thus, twelve steel threaded rods, crossing the RC elements in previously drilled holes, were used to equilibrate the reaction force resultant of the pressure applied by the airbags in the infill panel. The steel rods were strategically placed to evaluate the load distribution throughout the entire infilled RC frame resorting to load cells attached to each rod, which allowed continuously measuring the forces transmitted to the reaction structure where the rods were directly screwed to. On the other extremity of each tensioned rod, appropriate nuts and steel plates were used to anchor the rod and apply its reaction force on the concrete surface by uniformly distributed normal stresses, thus avoiding load concentration on the RC elements crossed by the rods.



a) b) c)

Fig. 3. Layout of the out-of-plane test setup, a) front, b) lateral and c) plan view: 0 - strong floor, 1 – foundation steel shape, 2 – high-strength rods (ø30mm) fixing the foundation steel shape to the reaction slab, 3 – steel rod (ø20mm) connecting the RC frame to the foundation steel shape, 4 – vertical high-strength rods (ø30mm) to apply axial load, 5 –steel cap, 6 - steel rods (ø20mm) connecting the RC frame and the reaction structure, 7 - distributing load plate, 8 - self-equilibrated reaction steel structure, 9 – counterweight, 10 – wood bars, 11 - hydraulic jack (for axial load application), 12 – vertical wooden platform, 13 – airbags, 14 – infill panel, 15 – RC column, 16 – steel plate for rod force distribution.

In each column the axial load was applied by means of a hydraulic jack inserted between a steel cap placed on the top of the column and an upper HEB steel shape, which, in turn, was connected to the foundation steel shape resorting to a pair of high-strength rods per column. Hinged connections were adopted between these rods and the top and foundation steel shapes; the axial load actually applied on the columns was continuously measured by load cells inserted between the jacks and the top of each column, which was paramount to perform in-plane tests.

a) b)

Fig. 4. General view of the experimental test setup a) Front view b) Lateral view.

The pressure level inside the airbags was set by two pressure valves which were controlled according to the target and measured out-of-plane displacement of the central point of the infill panel (the control node and variable) continuously acquired during the tests using a data acquisition and control system developed in National Instruments LabVIEW software platform. Prior to the experimental campaign itself, the calibration of the whole system was performed; this consisted in comparing the sum of load cells' forces with the airbag pressure resultant force (the pressure multiplied by the theoretical loaded panel area), in order to obtain the variation of load distribution, i.e. indirectly the actually loaded area, with the increase of distance between the steel reaction structure and the surface loaded panel. This calibration was made by inserting a vertical wooden panel supported in wood beams reacting against the RC top and bottom beams, thus without involving the brick masonry panel.

2.3. Instrumentation

The instrumentation of the experimental tests was composed by a total of 23 displacement transducers, amongst Linear Variable Displacement Transducers (LVDTs) and Draw Wire Transducers (DWTs), as illustrated in Fig. 5. Transducers were divided in 3 different groups according to the corresponding measurement objective: i) IM wall out-of-plane displacements (13 DWTs), ii) out-of-plane rotation between the infill panel and the surrounding RC frame (8 LVDTs) and iii) out-of-plane displacements of the RC frame (2 LVDTS).

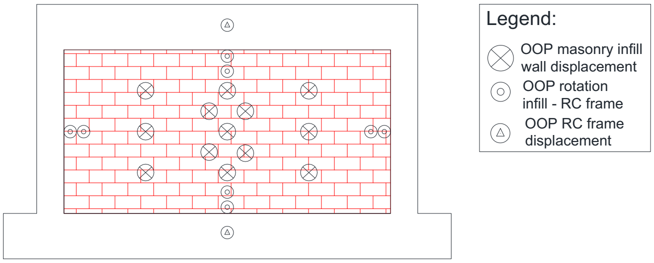


Fig. 5. Layout of the test instrumentation.

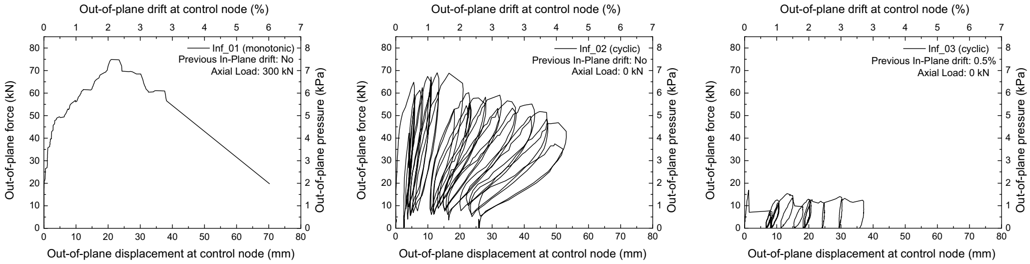
2.4. Loading condition

As previously stated, the aim of the present experimental campaign is to better understand the out-of-plane behaviour of IM walls, particularly when subjected to previous in-plane damage. In addition, the assessment of the influence of RC column axial load application in the out-of-plane response was made possible by imposing an axial load of 300kN on each RC column during Inf_01 test and no axial load applied in Inf_02 and Inf_03 tests.

The Inf_01 test was carried-out by imposing monotonic increasing out-of-plane displacements in the IM panel. Concerning the Inf_02 and Inf_03 tests, cyclic out-of-plane displacements were imposed on the IM wall with steadily increasing displacement levels, targeting the following nominal peak displacements: 2.5; 5; 7.5; 10; 15; 20; 25; 30; 35; 40; 45; 50; 50; 55; 60; 65 and 70 (mm). Three cycles were repeated for each lateral deformation demand level at the control node chosen as the central point of the IM wall where concentrated deformation is expected.

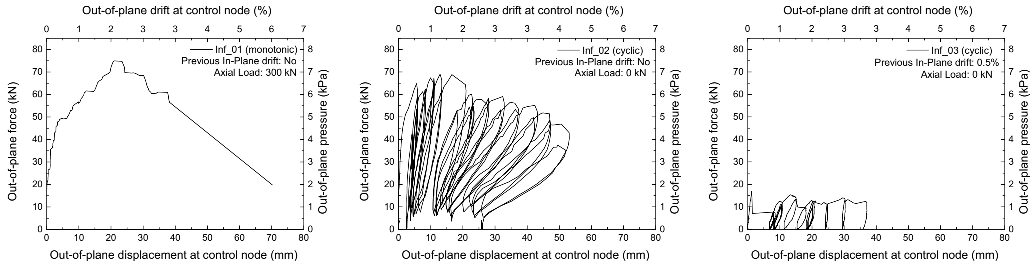
3. Results

The results of the out-of-plane tests for fully infilled RC frames without (Inf_01 and Inf_02) and with previous in-plane drift damage (Inf_03) were evaluated in terms of force-displacement hysteretic curves and are illustrated in



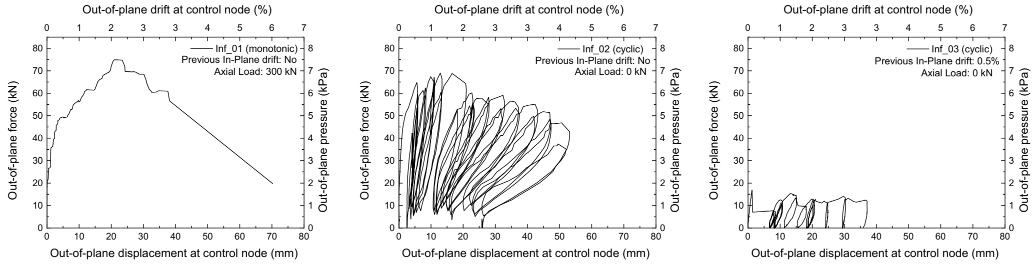
a) b) c)

Fig. 6a,



a) b) c)

Fig. 6b and



a) b) c)

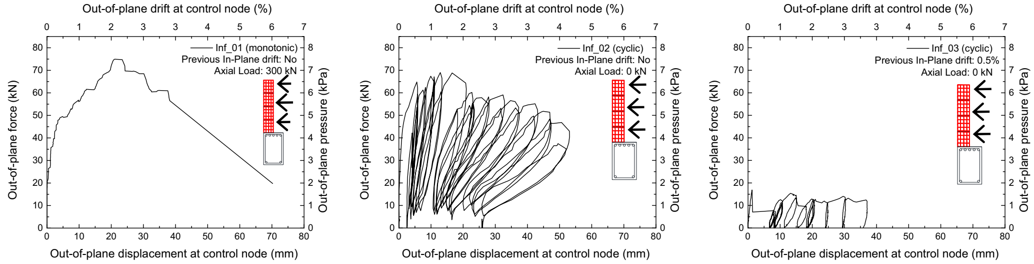
Fig. 6c, respectively. For a better comparison between the tests, Fig. 7 includes all the global force-displacement test results. From the result analysis, the following main observations can be drawn:

- The maximum strength was almost 4 times higher for tests without previous in-plane damage (Inf_01 and Inf_02) and for higher out-of-plane drift values. For Inf_01 and Inf_02 tests the maximum strength occurs at out-of-plane drift values between 1.5-2%, while for the Inf_03 test it occurs at 0.25% drift value;

- The strength degradation is particularly pronounced in the tests without in-plane damage (Inf_01 and Inf_02), while the strength degradation in test Inf_03 was found much reduced during the entire test. This fact can be explained by the failure mode observed in this test (described below);

- The initial stiffness showed to be significantly affected by existing in-plane damage. In the Inf_03 test (with previous in-plane damage), the initial stiffness is almost 30% lower than for the original IM walls. By contrast, the comparison of results of Inf_01 and Inf_02 evidenced that the initial stiffness of IM walls was little influenced by the axial load in RC columns, since the test with axial load (Inf_01) had about 5% more initial stiffness when compared with the Inf_02;

- Concerning the tests without previous in-plane damage, the initial cracking was found for lower out-of-plane drift values (about 0.1% drift) for the Inf_02 test. The cracking force in both experimental tests was about 50kN. In the test with previous in-plane damage (Inf_03), the initial cracking occurs for 0.1% drift and at maximum strength of 18kN.



a) b) c)

Fig. 6. Out-of-plane force-displacement test results: a) Inf_01 b) Inf_02 and c) Inf_03.

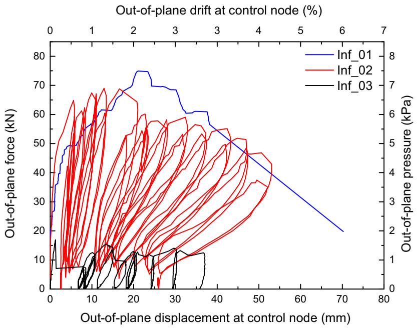
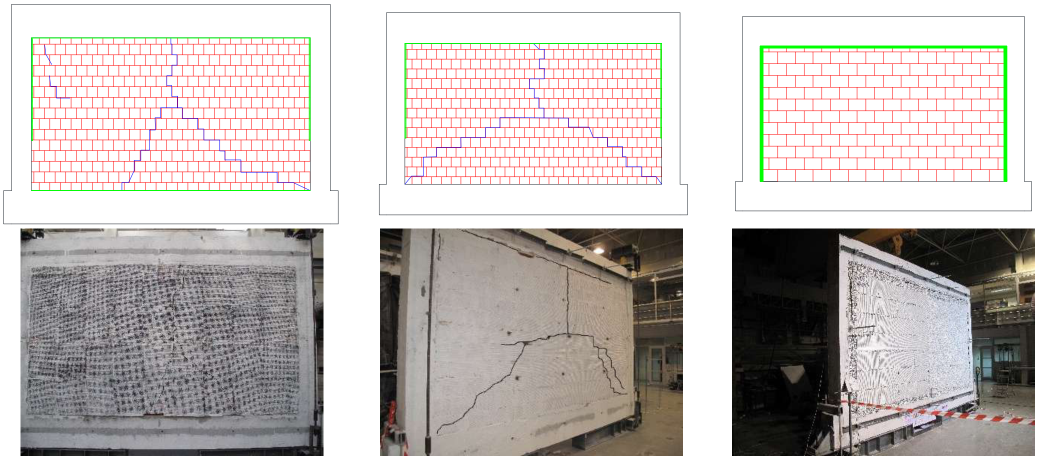


Fig. 7. Out-of-plane force-displacement test results: Global results.

Aiming at a detailed observation of the damage evolution during the experimental tests within the present work testing campaign, each test was stopped at the end of the last cycle of each displacement level in order to highlight and register new cracks and/or the evolution of existing ones. Visual observation of the damage evolution during the tests yielded the information described in the following paragraphs. The final damage patterns of all tests are presented in Fig. 8, showing several differences between tests with and without previous in-plane damage. The final cracking shape of the Inf_01 was vertical, with detachment between the infill panel and the surrounding RC frame in the top and bottom joints, as shown in Fig. 8a. However, the Inf_02 test exhibited a trilinear cracking pattern with deformation concentrated in the mid-point of the wall, with slight cracking in the top joint, as illustrated in Fig. 8b. Finally, it was found that no cracking pattern occurred in the middle of the IM wall Inf_03, which is related with the observed detachment between the infill panel and the surrounding top beam and columns, evidencing typical rigid body behaviour (Fig. 8c).



a) b) c)

Fig. 8 – Final cracking pattern and pictures for the three out-of-plane tests: a) Inf_01, b) Inf_02 and c) Inf_03.

4. Conclusions

This paper reports an experimental campaign carried out at the Laboratory of Earthquake Engineering at the Faculty of Engineering of University of Porto in order to study the out-of-plane behaviour of IM walls, and the influence of the previous in-plane drift in their out-of-plane response. For this, three full-scale infill panels were constructed and were subjected to out-of-plane monotonic and cyclic loading, with and without previous in-plane drift. The out-of-plane loading was applied using an innovative structure that was specially built to perform this type of tests. The experimental test setup was presented, including all the instrumentation and loading conditions.

A significant difference was found between tests' results, with and without previous in-plane damage, namely: a) the maximum strength was almost 4 times higher for the tests without previous in-plane damage, and for higher out-of-plane drift values; b) a significant reduction of the initial stiffness was observed in the test with previous in-plane damage when compared with the other ones; c) a significant maximum strength reduction was found in the tests without the previous in-plane damage, which was not verified in the Inf_03.

The failure modes observed in each of the tests reveals different out-of-plane behaviour of the IM walls with and without previous in-plane damages. The tests in original IM walls (Inf_01 and Inf_02) showed vertical cracking, with detachment between the infill panel and the surrounding RC frame in the top and bottom joints. In the Inf_02 wall a trilinear cracking was observed with concentrated deformation in the middle point of the wall, with slight cracking in the top joint. For the test with previous in-plane damage only the detachment was observed between the infill panel and the surrounding top beam and columns, and typical rigid body behaviour was found

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References

[1] H. Rodrigues, X. Romão, A. G. Costa, A. Arêde, H. Varum, J. Guedes*, et al.*, "Sismo de L'Aquila de 6 de Abril de 2009. Ensinamentos para Portugal," presented at the 8º Congresso Nacional de Sismologia e Engenharia Sísmica - SISMICA 2010, Aveiro, 2010.

[2] X. Romão, A.A.Costa, E. Paupério, H. Rodrigues, R. Vicente, H. Varum*, et al.*, "Field observations and interpretation of the structural performance of constructions after the 11 May 2011 Lorca earthquake," *Engineering Failure Analysis,* vol. 34, pp. 670-692, 2013.

[3] A. Penna, P. Morandi, M. Rota, F. Manzini, F. Porto, and G. Magenes, "Performance of masonry buildings during the Emilia 2012 earthquake," *Bull Earthquake Eng,* vol. 12, pp. 2255-2273, 2014.

[4] G. Calvi and D. Bolognini, "Seismic response of reinforced concrete frames infilled with weakly reinforced masonry panels," *Journal of Earthquake Engineering,* vol. 5, pp. 153-185, 2001.

[5] S. Hak, P. Morandi, and G. Magenes, "Out-of-plane experimental response of strong masonry infills," presented at the Second European Conference on Earthquake Engineering and Seismology, Istanbull, 2014.

[6] A. Furtado, H. Rodrigues, A. Arêde, and C. Costa, "Geometric characterization of Portuguese RC buildings with masonry infill walls (*In Press*)," *European Journal of Environmental and Civil Engineering,* 2015.